Estimation of head rice yield by measuring the bending strength of kernels after drying by different drying methods

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Abstract: In this study, two local rough rice cultivars (long and medium grain) were dried by three different drying methods including indirect and mixed-mode active solar dryers, and continuous dryer at three temperature levels of 35 ℃, 45 ℃ and 55 ℃. Bending strength of brown rice kernels, percentage of fissured kernels and head rice yield were measured and evaluated. No significant difference between bending strength of dried rough rice kernels by indirect and mixed-mode active solar drying methods was observed. Drying by continuous dryer improved the mechanical strength of kernels by providing tempering periods. Medium size kernels depicted more strength than longer ones. Strong relationships were established between the bending strength of the brown rice kernels and percentage of fissured kernels and as well as head rice yield.

Keywords: bending strength, drying, head rice yield, fissured kernels, rough rice

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1 Introduction

Rice as one of the most important cereals is ranked as the highest demanded food grains. Population growth and food resource limitations force to reduce rice production wastes. Breakage of kernels during milling process is a major problem for rice processing. Clement and Seguy (1994) stated that long and narrow rice grains break during milling process. However, it was reported that most rough rice losses are produced in drying process (Brooker et al., 1992; Cnossen and Siebenmorgen, 2000). Thermal and moisture content gradients during rough rice drying produce stresses within kernels. When these stresses exceed the kernel strength limit, fissures are created and developed in kernels, resulting in kernel failure (Yang et al., 2002; Siebenmorgen and Qin, 2005; Prachayawarakorn et al., 2005). Therefore, drying is known as a critical operation amongst rough rice processing operations.

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Mechanical behavior of agricultural materials under force is generally determined by force-deformation (stress-strain) test (Mohsenin, 1996). Efforts have been made to explain the breakage of rice kernel using its mechanical properties (Lu and Siebenmorgen, 1995; Siebenmorgen and Qin, 2005; Siebenmorgen et al., 2005). Siebenmorgen and Qin (2005) reported that HRY is not a function of average breaking force of rice kernels and has strong correlation with percentage of "strong" kernels, which is defined as kernels that sustained 20 N forces at bending. Moreover, a significant relationship between HRY and the percentage of kernels that tolerated breaking force greater than 20 N (strong kernels) was reported by Siebenmorgen et al. (2005). Zhang et al. (2005) found that mechanical properties of fissured brown rice kernels measured by three-point bending test were smaller than those of sound ones. The same results were reported by researchers on some Iranian rice cultivars (Afkari-Sayyah and Minaei, 2004; Kermai et al., 2006a; Kermani et al., 2006b; Hoseinian et al., 2008; Mahfeli et al., 2014). It was concluded that bending strength considers morphological properties of rice kernels to predict HRY.

The objectives of the present study were: 1) to compare the bending strength of kernels of two local rice cultivars after drying in different dryers; and 2) to find a relationship for estimating HRY using mechanical properties of the kernels.

2 Materials and methods

Two local rough rice cultivars of medium size grains (Lenjan) and long size grains (Fajr) were collected from farm in Oct. 2010. Initial moisture content was measured by gravimetric method in an air-oven at 105℃ for 24 h (AOAC, 2000), and was 18% and 17% (w.b.) for Lenjan and Fajr cultivars, respectively. The grains were immediately sealed in air tight plastic bags, stored in cool place for 12 h to reduce field heat gradually, and then kept in a refrigerator at 5℃. Samples were removed from the refrigerator and kept at ambient temperature (about 20℃) for 12 h before drying. Moisture content of the samples was measured before and after each drying treatment by gravimetric method. One hundred kernels were randomly selected from each sample and hulled manually. Physical characteristics (length, width, thickness, slenderness, and the weight of 1000 kernels) of brown rice kernels were measured using a digital caliper (500, Mitutoyo, Japan) with an accuracy of ±0.01 mm.

2.1 Drying systems

Three different drying systems were used for drying samples. Final moisture content of samples was considered to be 10.5±0.5% as recommended by Sadeghi and Nassiri (2010). Dried rough rice samples were sealed in plastic bags and stored at ambient temperature before they were used for three-point bending tests.

2.1.1 Continuous drying system

Paddy was dried by a laboratory inclined bed continuous dryer, in which two screen sheets as a drying bed were fixed 20 mm apart (Zomorodian and Allameh, 2003). Drying air at three levels of 35℃, 45℃ and 55℃ was passed through the rough rice in transverse direction at the rate of 0.28 kg/m^{2}s. Air temperature was controlled by PT-100 sensor based thermostat. About 1600 g rough rice fed into the dryer from top hopper. The flow rate of paddy in dryer was controlled by a multi-vane rotary gate at the bottom of the dryer (Figure 1). Discharged grains were refilled in hopper, manually. In each run every few minutes, the moisture content was measured by a portable moisture meter (Rasa 3000, ±1% accuracy).

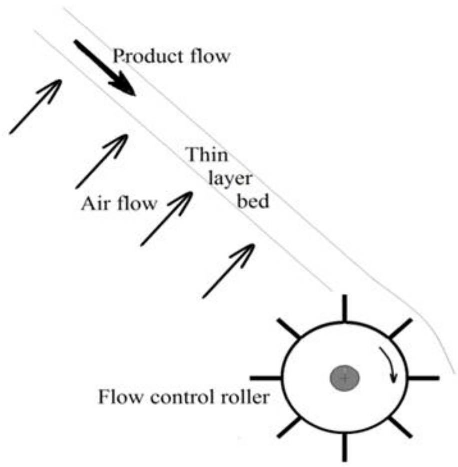

Figure 1 Schematic diagram of continuous dryer

2.1.2 Indirect active solar drying system

A cabinet dryer was equipped by a 1500×550 mm flat solar collector. The collector was mounted on proper portable frame and tilted 45° towards the south (with altitude of 29.7°) (Duffie and Beckman, 1991). A plywood board covered the grain bed container to prevent direct solar radiation on grains. A part of the solar collector surface was covered by white foam sheet for regulating the drying air temperature about pre-adjusted levels, namely, 35℃, 45℃ and 55℃. A 375 W electrical heater was also used to prepare a constant drying temperature at necessary occasions (cloudy sky). Volumetric air flow rate was the same as previous dryer (0.28 kg/m^{2}s). About 850 g paddy was spread over the dryer tray in 20 mm thickness and placed into the dryer chamber (Figure 2).

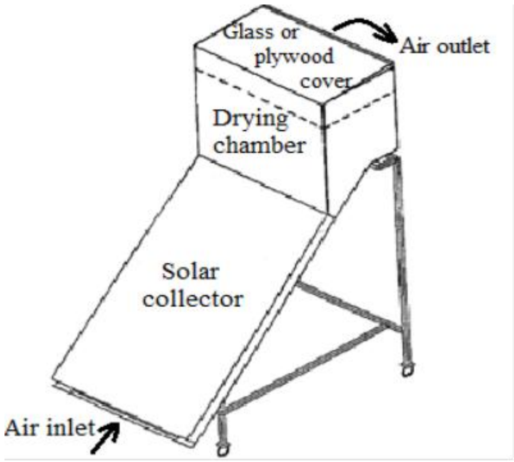

Figure 2 Schematic diagram of indirect and mixed-mode solar dryer

2.1.3 Mixed-mode active solar drying system

The procedure was the same as indirect active solar dryer, except that the sun rays also radiated directly on grains in tray.

2.2 Three-point bending test

Three-point bending test was applied on each kernel using an Instron machine (Santam, STM–20) equipped with a load cell of 50 kgf (BONGSHIN, DBBP-50, Korea). A hundred rough rice grains were randomly selected from each treatment batch and dehusked manually to minimize any likely mechanical damages. Then, the brown rice kernels were prepared for bending tests. Loading probe had a thickness of 1.5 mm with flat surface. The support points were 3.4 mm apart (Figure 3). Tests were run at constant deformation rate of 0.5 mm/s (Siebenmorgen et al., 2005). The breaking force was recorded for samples and corresponding bending stress was calculated to normalize the variations in kernel cross section areas (ASAE, 2002). It can be calculated by Equation 1 :

$$\sigma = \frac{FLC}{4I} \tag{1}$$

where σ is bending strength, Pa; F is breaking (peak) force, N; L is distance between the supports, m; c is distance from the neutral axis to the outer surface of the particle, m; for a rice kernel, c=d/2 where d is the minor diameter of the ellipse or thickness of the kernel), and I is area moment of inertia, m^4. It was assumed that the cross sectional area perpendicular to the longitudinal axis of rice kernel is an ellipse; therefore, area moment of inertia was calculated by $I=0.049(bd^3)$, where b is the major diameter of the ellipse or width of the rice kernel.

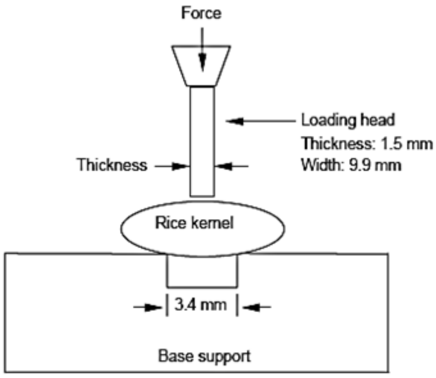

Figure 3 Loading probe, support and rice kernel

2.3 Milling quality

Processing quality of rough rice is expressed by the percentage of head rice yield (HRY) and fissured kernels after milling process (Aquerreta et al., 2007). Consequently, a crack tester device was used to measure the percentage of fissured kernels. This device (RT20, Iran) consisted of a fluorescent lamp, and was installed under the lattice metal sheet with longitudinal grooves. Rice kernels were placed on grooves longitudinally and inspected simply and carefully by a magnifying glass. Fifty kernels were randomly selected from each sample with triplicates (totally 150 kernels), and dehusked manually to determine the percentage of initial fissures.

Samples of 50 g were shelled using a laboratory scale rubber roll type husker (Model THU-35A, Satake, Japan). Brown rice was milled for 30 s by a Kett rice polisher (Kett Electric Laboratory, Tokyo, Japan) for removing the bran. Percentage of HRY (white kernels having 3/4 or more of the original kernel length) was calculated as ratio of the mass of whole white rice kernels to the total mass of rough rice (Aquerreta et al., 2007; Yadav and Jindal, 2008). This ratio was determined in samples of 10 g of white rice.

2.4 Statistical analyses

Analysis of variance (ANOVA) and comparison of means by Duncan multiple range posttest was performed using SPSS software (release16, SPSS software Inc.). The experimental design flow chart is shown in Figure 4. Relationship between mechanical property of kernels and percentage of fissured kernels as well as mechanical property and percentage of HRY was established using regression analysis technique.

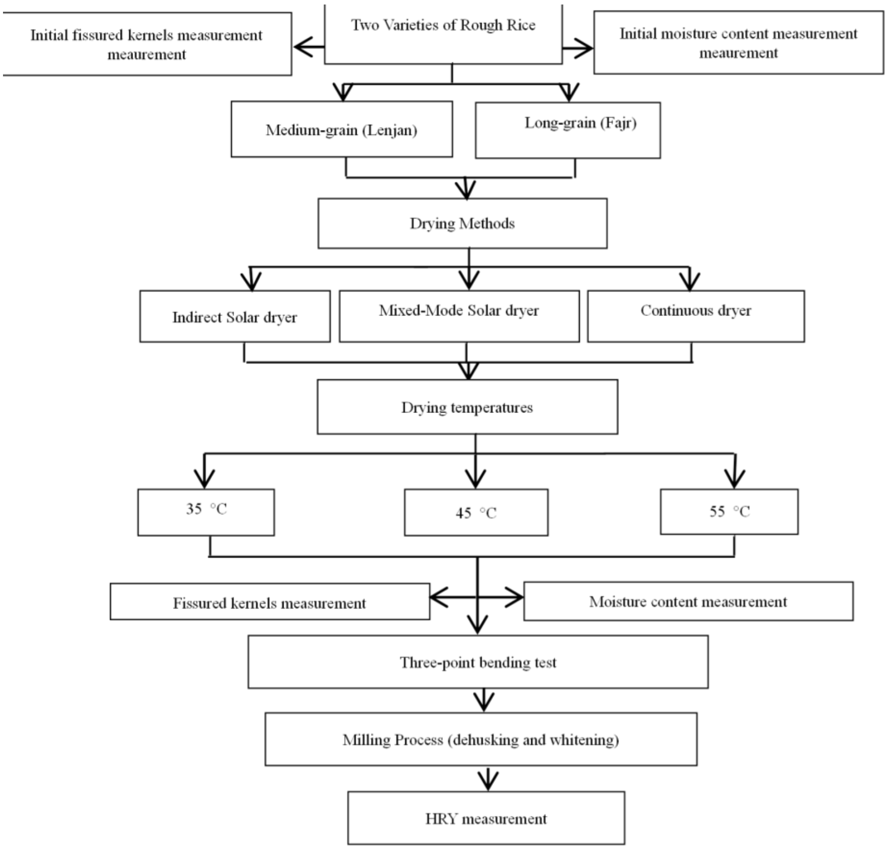

Figure 4 Experimental design flow chart.

3. Results and discussion

3.1 Morphological properties

Some kernels' physical properties for both brown rice cultivars are given in Table 1. Slenderness (the ratio of length to diameter) of Fajr kernels was significantly higher as compared to Lenjan cultivar (p<0.05).

3.2 Bending strength

All experimental main factors (cultivar, drying air temperature and method) significantly affected the strength of brown rice kernels (P <0.01) with non-significant interaction effects (P> 0.1).

Table 1 Some morphological characteristics of grain brown rice

Variety	Length, mm	Width, mm	Thickness, mm	Length/width	1000 kernels mass, g
Medium grain (Lenjan)	6.0±0.4	2.3±0.2	1.6±0.1	2.7±0.3	15.8±0.5
Long grain (Fajr)	7.3±0.2	1.9±0.1	1.7±0.1	3.8±0.2	17.9±0.3

Note: Table values show the mean ±standard deviation.

Medium size rice kernels (Lenjan) tolerated higher bending strength than long ones (Fajr) as is shown in Table 2. This might be mainly due to the texture of cultivars which resulted in different growth conditions. Ambient temperature during grain development especially in grain reproductive stage plays an important role in rice grain quality (Cooper et al., 2006; Peng et al., 2004). On the other hand, Clement and Seguy (1994) reported that longer rice grains collapse under applied force more easily.

Table 2 Bending strength in all treatments for two rough rice cultivars

Paddy variety	Treatments		Bending strength, MPa	Paddy variety	Treatments		Bending strength, MPa
	Drying method	Drying temperature, ℃			Drying method	Drying temperature, ℃	
Lenjan	Continuous	35	10.5 ^{a}	Fajr	Continuous	35	7.5 ^{ab}
		45	9.6 ^{ab}			45	6.8 ^{bc}
		55	8.6 $^{a-c}$			55	5.z4 ^{c}
	Mixed solar	35	8.4 ^{bc}		Mixed solar	35	5.5 ^{bc}
		45	8.3 ^{bc}			45	5.4 ^{c}
		55	7.5 ^{cd}			55	5.3 ^{c}
	Indirect solar	35	8.0 ^{bc}		Indirect solar	35	6.1 ^{b}
		45	8.9 $^{a-c}$			45	5.9 ^{bc}
		55	5.5 ^{d}			55	5.0 ^{c}
	Mean		**8.4 ^{A}**		**Mean**		**5.8 ^{B}**

Note: The mean values of bending strength for each cultivars with the same small and capital letters are not significantly different (P >0.05)

Comparison among the bending strength means at different temperature levels showed a non-significant difference at 35 ℃ and 45 ℃ (P>0.05). Kernels tend to become weaker at highest drying temperature (55^{o}C) due to created thermal stresses. This gradient produced and developed fissures in kernels (Courtois et al., 2001; Iguaz et al., 2006; Kermani et al., 2006) (Table 2 and Table 3).

Table 3 Mean values of bending strength

Drying method	Drying Temperature, ℃			Mean
	35	**45**	**55**	
Continuous	9.1	8.3	6.8	**8.1 ^{A}**
Mixed solar	7.1	6.9	6.4	**6.8 ^{B}**
Indirect solar	7.5	7	5.3	**6.6 ^{B}**
Mean	**7.8 ^{a}**	**7.5 ^{a}**	**6.2 ^{b}**	

Note: The mean values with the same small or capital letters are not significantly different (P >0.05)

Direct solar radiation has not influenced the strength of kernels as concluded from non-significant difference between bending strength of kernels for indirect and mixed-mode active solar dryers. However, bending strength of kernels dried by continuous dryer drastically increased due to alternative heating periods while unloading and reloading the drier. Renjie et al. (2010) reported that tempering has a significant influence on the moisture content gradient in kernels. Tempering reduces heat fluxes and avoids crack development within kernels.

The most bending strength of 10.5 MPa among all treatments was obtained for Lenjan cultivar when dried in continuous dryer at 35 ℃ because of low rate drying. The least strength for the same cultivar was observed for indirect solar drying method at 55 ℃. Corresponding values were 7.5 MPa and 5 MPa for Fajr cultivar at 35 ℃ and 55 ℃.

To pinpoint on kernels' strength, distribution of bending strength frequencies were determined (Figure 5 and Figure 6). This is a typical curve for both cultivars when dried in continuous dryer at 45^{o}C. Both curves followed the bi-modal pattern. The same patterns were observed for all treatments. Some researchers classified rice kernels into two groups "strong" and "weak" based on bi-modal strength pattern (Lu and Siebenmorgen, 1995; Siebenmorgen and Qin, 2005; Siebenmorgen et al., 2005). It was reported that the strength of grains while processing is function of percentage of strong grain in batch.

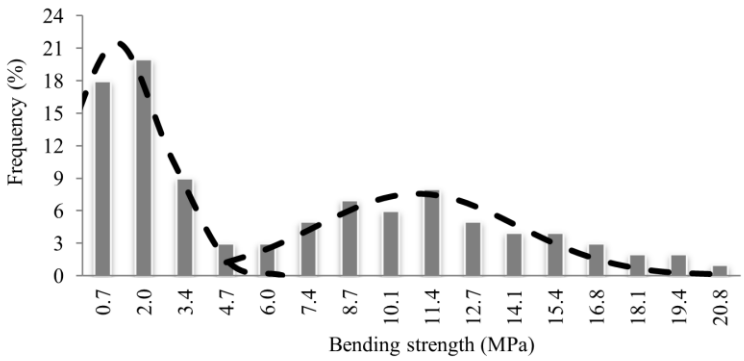

Figure 5 Frequency histograms approximated by two normal distributions (Long grain variety (Fajr) dried in continuous dryer at 45 ℃)

By approximation of normal distribution for each group, a discrimination threshold value was determined in the range of mean plus a standard deviation for the first normal distribution and mean minus a standard deviation of the second normal distribution. This range was nearly 4 MPa to 6 MPa for all treatments. Therefore, the mean strength of 5 MPa was taken as threshold value for classifying the kernels into two groups which hereafter are called "weak" and "strong" kernels. Percentage of kernels that possessed bending strength more than 4 MPa, 5 MPa and 6 MPa are given in Table 4. It shows that 5 MPa threshold point was chosen suitably.

3.3 Estimation of HRY

Percentage of fissured kernels and HRY were determined for all treatments (Table 5), and then the correlation between bending strength of kernels and percentage of fissured kernels, and also HRY(%) were calculated (Table 6).

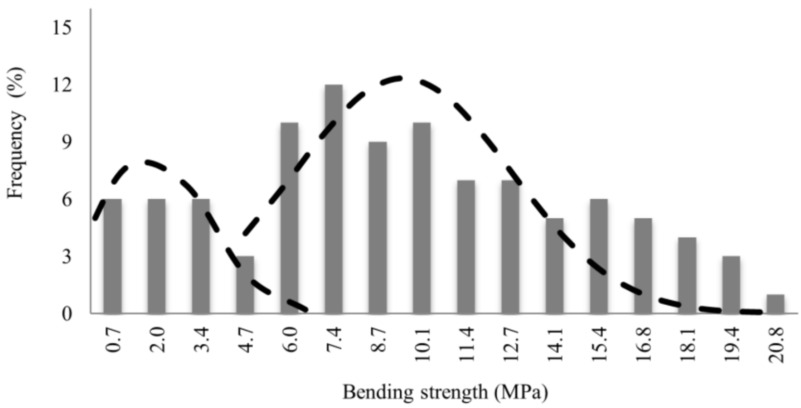

Figure 6 Frequency histograms approximated by two normal distributions (Medium grain variety (Lenjan) dried in continuous dryer at 45 ℃)

Table 4 Percentage of kernels with bending strength more than 4, 5 and 6 MPa for different treatments

Paddy variety	Treatments		Percentage of kernels with strength more than		
	Drying method	**Drying temperature, ℃**	**4 Mpa**	**5 Mpa**	**6 Mpa**
Medium grain (Lenjan)	Continuous	35	90	83	82
		45	84	79	74
		55	75	69	67
	Mixed solar	35	88	86	76
		45	83	78	71
		55	55	50	49
	Indirect solar	35	85	84	77
		45	79	77	74
		55	52	47	45
	Mean		**76.8**	**72.6**	**68.3**
Long grain (Fajr)	Continuous	35	58	57	50
		45	51	50	45
		55	48	46	40
	Mixed solar	35	54	53	44
		45	46	45	38
		55	39	40	32
	Indirect solar	35	58	54	50
		45	46	45	41
		55	39	35	31
	Mean		**48.8**	**47.2**	**41.2**

Considering the correlation coefficients values, linear equations were established between aforementioned parameters as given in Table 7 and Table 8. According to the relationships, the grains that sustain 5 MPa stress, and even more, can likely pass milling process safely. Sharma and Kunze (1982) stated that the grain with a fissure is likely broken when it is milled.

Table 5 Percentage of fissured kernels and HRY for different treatments

Paddy variety	Treatments		Percentage of fissured kernels	Percentage of head rice yield
	Drying method	**Drying temperature, ℃**		
Medium grain (Lenjan)	Continuous	35	13.3	57.8
		45	14.7	61.5
		55	36.0	35.8
	Mixed solar	35	13.0	63.8
		45	23.7	56.6
		55	55.0	16.6
	Indirect solar	35	12.0	62.2
		45	23.3	53.0
		55	66.0	19.3
	Mean		**28.6**	**47.4**
Long grain (Fajr)	Continuous	35	49.0	30.1
		45	51.0	25.3
		55	65.0	21.9
	Mixed solar	35	50.7	25.8
		45	61.0	22.2
		55	74.0	18.1
	Indirect solar	35	55.0	25.8
		45	60.3	21.5
		55	74.0	19.2
	Mean		**60.0**	**23.3**

Table 6 Correlation coefficient and root mean squared of error (RMSE) between bending strength and either percentage of fissured kernels and HRY

Parameter	Variety	Bending strength			
		Mean	>4 MPa	>5 MPa	>6 MPa
Fissured	Lenjan	-0.79 (12.1)	-0.98 (4.1)	**-0.99 (3.3)**	-0.98 (4.5)
	Fajr	-0.76 (6.7)	-0.91 (4.3)	**-0.93 (3.7)**	-0.92 (4.1)
HRY	Lenjan	0.69 (14.5)	0.96 (5.4)	**0.98 (4.2)**	0.94 (6.7)
	Fajr	0.72 (5.6)	0.92 (3.1)	**0.93 (3.0)**	0.93 (2.9)

Table 7 Relationship between percentage of fissured kernels and bending strength

Paddy variety	Drying method	Equation (Adjusted coefficient of determination)
Medium grain (Lenjan)	Continuous	$FK = -1.7\ SK_5 + 153.6$ ($R^2 = 0.949$)
	Mixed solar	$FK = -1.2\ SK_5 + 112.9$ ($R^2 = 0.998$)
	Indirect solar	$FK = -1.4\ SK_5 + 134.2$ ($R^2 = 0.999$)
Long grain (Fajr)	Continuous	$FK = -1.3\ SK_5 + 122.5$ ($R^2 = 0.713$)
	Mixed solar	$FK = -1.7\ SK_5 + 142.3$ ($R^2 = 0.961$)
	Indirect solar	$FK = -1.0\ SK_5 + 108.1$ ($R^2 = 0.953$)

Note: FK and SK_5 refer to percentage of fissured kernels and percentage of kernels that sustained bending strength more than 5 MPa, respectively.

Table 8 Relationship between percentage of HRY and bending strength

Paddy variety	Drying method	Equation (Adjusted coefficient of determination)
Lenjan	Continuous	$HRY = 1.8\ SK_5 - 84.3$ ($R^2 = 0.838$)
	Mixed solar	$HRY = 1.3\ SK_5 - 50.0$ ($R^2 = 0.994$)
	Indirect solar	$HRY = 1.1\ SK_5 - 34.9$ ($R^2 = 0.999$)
Fajr	Continuous	$HRY = 0.7\ SK_5 - 11.8$ ($R^2 = 0.997$)
	Mixed solar	$HRY = 1.3\ SK_5 - 39.9$ ($R^2 = 0.802$)
	Indirect solar	$HRY = 0.9\ SK_5 - 20.3$ ($R^2 = 0.942$)

Note: HRY and SK_5 refer to percentage of fissured kernels and percentage of kernels that sustained bending strength more than 5 MPa, respectively.

4 Conclusion

The study revealed that the strength of grains of two rough rice cultivars followed the same trend when dried by different drying methods. Highest head rice yield was obtained when both cultivars were dried in a continuous dryer. Frequency distribution of bending strength for both cultivars depicted two distinct modes for classifying strong and weak kernels. There was a strong linear relation between the percentage of kernels having bending strength more than 5 MPa and the percentage of fissured kernels. Likewise, a strong relationship was established between bending strength and percentage of head rice yield.

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